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Selecting the "Touched Vertebra" as the Lowest Instrumented Vertebra in Patients with Lenke Type-1 and 2 Curves

Radiographic Results After a Minimum 5-Year Follow-up

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Background: The selection of the lowest instrumented vertebra (LIV) in patients with adolescent idiopathic scoliosis (AIS) is still controversial. Although multiple radiographic methods have been proposed, there is no universally accepted guideline for appropriate selection of the LIV. We developed a simple and reproducible method for selection of the LIV in patients with Lenke type-1 (main thoracic) and 2 (double thoracic) curves and investigated its effectiveness in producing optimal positioning of the LIV at 5 years of follow-up.

Methods: The radiographs for 299 patients with Lenke type-1 or 2 AIS curves that were included in a multicenter database were evaluated after a minimum duration of follow-up of 5 years. The "touched vertebra" (TV) was selected on preoperative radiographs by 2 independent examiners. The LIV on postoperative radiographs was compared with the preoperative TV. The final LIV position in relation to the center sacral vertical line (CSVL) was assessed. The CSVL-LIV distance and coronal balance in patients who had fusion to the TV were compared with those in patients who had fusion cephalad and caudad to the TV. The sagittal plane was also reviewed.

Results: In 86.6% of patients, the LIV was selected at or immediately adjacent to the TV. Among patients with an "A" lumbar modifier, those who had fusion cephalad to the TV had a significantly greater CSVL-LIV distance than those who had fusion to the TV (p = 0.006) or caudad to the TV (p = 0.002). In the groups with "B" (p = 0.424) and "C" (p = 0.326) lumbar modifiers, there were no differences among the TV groups.

Conclusions: We recommend the TV rule as a third modifier in the Lenke AIS classification system. Selecting the TV as the LIV in patients with Lenke type-1 and 2 curves provides acceptable positioning of the LIV at long-term follow-up. The position of the LIV was not different when fusion was performed caudad to the TV but came at the expense of fewer motion segments. Patients with lumbar modifier "A" who had fusion cephalad to the TV had greater translation of the LIV, putting these patients at risk for poor long-term outcomes.

Level of Evidence: Therapeutic Level III. See Instructions for Authors for a complete description of levels of evidence.

The aim of surgical treatment of adolescent idiopathic scoliosis (AIS) is to achieve 3-dimensional correction of the deformity while minimizing the number of levels fused. Advances in instrumentation and surgical techniques allow substantial correction, yet there is no universally accepted guideline for selection of the upper and lower instrumented vertebrae[1-19].

The decision regarding where to end the fusion in patients with AIS is pivotal in order to avoid adding-on and

*A list of the Harms Study Group Investigators is provided in a note at the end of the article.

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coronal or sagittal decompensation. Multiple authors have suggested identifying the lowest instrumented vertebra (LIV) on the basis of diverse radiographic parameters, including the location within the stable zone, vertebral neutrality, the absence of kyphosis, adjacent disc angulations, curve flexibility, and stable vertebra (SV) location, but none of these rules are universally recognized[1-8,20,21]. Ideally, there would be a simple and reproducible way to identify the appropriate caudad fusion level that would provide acceptable long-term results.

Since their early development, AIS classification systems have helped to ascertain which curves to include in the fusion, whereas specific recommendations for LIV selection are not well defined. King et al.[7] developed a classification system to assist in the selection of fusion levels for patients with thoracic AIS but did not address sagittal alignment. This classification system also demonstrated fair to poor reliability[20,21]. Subsequently Lenke et al.[20] developed a classification system that considered both coronal and sagittal alignment while providing criteria to determine which curves should be included in the fusion. This classification system showed improved reliability, but it did not provide a definite recommendation for selection of the optimum LIV. In this system, Lenke et al. introduced modifiers for the thoracic sagittal profile and coronal lumbar position. The thoracic sagittal modifier considers T5-T12 kyphosis and subdivides curves on the basis of that measurement, with hypokyphosis defined as <10°, normal kyphosis defined as 10° to 40°, and hyperkyphosis defined as >40°. The coronal lumbar spine modifier considers where the center sacral vertical line (CSVL) intersects the apical lumbar vertebra, with "A" indicating that the CSVL falls between the apical pedicles, "B" indicating that the CSVL touches the medial apical pedicle or vertebral body corner, and "C" indicating that the CSVL falls medial to the lateral aspect of the lumbar apical vertebral body (or bodies, if the apex is a disc). The "touched vertebra" (TV), initially described by Lenke, Newton, and colleagues[9], is defined as the most cephalad thoracolumbar or lumbar vertebra (T12-L5) that is "touched" by the CSVL on any portion of the vertebra. We present the TV as the third modifier of the Lenke classification system. The purpose of the present study was to evaluate the effectiveness of this TV modifier in producing optimal long-term positioning of the LIV and global coronal balance at a minimum of 5 years of follow-up in a group of patients with Lenke type-1 (main thoracic) and 2 (double thoracic) curves.

Materials and Methods

The records for patients with Lenke type-1 and 2 AIS curves were obtained from a multicenter case registry. Each center obtained institutional review board approval. Only patients with a minimum of 5 years of follow-up were included. The CSVL was drawn on the upright preoperative and 5-year postoperative full-spine coronal radiographs. The TV was assessed by 2 experienced examiners (an attending spinal deformity surgeon and spine deformity researcher, both with >25 years of experience) on the preoperative radiographs, and the results were confirmed on the basis of agreement. The fusion level was determined for each patient at the discretion of the treating surgeon, who submitted the case to the database prior to the initiation of the present study. Preoperative and 5-year postoperative radiographs were compared, and the LIV-to-TV relationship was established. Three categories were identified: (1) fusion cephalad to the TV, (2) fusion to the TV, and (3) fusion caudad to the TV. These categories were then subdivided into 5 subgroups: LIV >1 level cephalad to the TV (TV>−1), LIV 1 level cephalad to the TV (TV−1), LIV at the same level as the TV (TV0), LIV 1 level caudad to the TV (TV+1), and LIV >1 level caudad to the TV (TV>+1).

With the assumption that the ideal LIV should be positioned over the center of the sacrum and bisected by the CSVL, the distance from the CSVL to the midpoint of the body of the LIV was measured on 5-year postoperative coronal radiographs. This distance was analyzed for the groups that had fusion cephalad to, caudad to, or at the level of the TV for each preoperative lumbar modifier subgroup (A, B, or C), and the groups were compared with analysis of variance (ANOVA). In addition, preoperative and 5-year postoperative lateral radiographs for all patients were reviewed by the senior author (L.G.L.) to determine if the preoperative sagittal stable vertebra (SSV) would influence the selection of the LIV. The SSV was defined as the vertebral level in which ≥50% of the vertebral body lies ventral to the posterior sacral vertical line (PSVL)[19]. Distal junctional kyphosis was defined as a change of ≥10° between the superior end plate of the LIV and the inferior end plate of the vertebra below it on a standing lateral full-spine radiograph[22].

Results

A total of 299 patients with AIS (including 207 with Lenke type-1 curves and 92 with Lenke type-2 curves) with ≥5 years of follow-up were available for review. Of the 299 patients, 161 (54%) had an "A" lumbar modifier, 76 (25%) had a "B" lumbar modifier, and 62 (21%) had a "C" lumbar modifier preoperatively. On postoperative radiographs, 50 patients (17%) had fusion cephalad to the TV, 153 (51%) had fusion to the TV, and 96 (32%) had fusion caudad to the TV. Six patients (2%) had

TABLE I Five-Year Postoperative CSVL-LIV Distance According to TV Group*

TV-LIV	No. of Patients	CSVL-LIV Distance† *(cm)*
TV≥−1 (LIV cephalad to TV)	50 (17%)	1.55 ± 1.18
TV0 (LIV at level of TV)	153 (51%)	1.26 ± 0.93
TV≥+1 (LIV caudad to TV)	96 (32%)	1.15 ± 0.87
Total	299 (100%)	1.27 ± 0.96

*CSVL = center sacral vertical line, LIV = lowest instrumented vertebra, and TV = touched vertebra. †The values are given as the mean and the standard deviation. P = 0.055 when comparing the CSVL-LIV distances among groups.

TABLE II Five-Year Postoperative CSVL-LIV Distance According to Lumbar Modifier*

TV-LIV	Preop. Lumbar Modifier "A" (N = 161)		Preop. Lumbar Modifier "B" (N = 76)		Preop. Lumbar Modifier "C" (N = 62)	
	No. of Patients	CSVL-LIV Distance† *(cm)*	No. of Patients	CSVL-LIV Distance†‡ *(cm)*	No. of Patients	CSVL-LIV Distance†§ *(cm)*
TV≥−1 (LIV cephalad to TV)	21 (13%)	2.01 ± 1.48	8 (11%)	1.13 ± 1.01	21 (34%)	1.24 ± 0.69
TV0 (LIV at level of TV)	97 (60%)	1.25 ± 0.93#	35 (46%)	1.27 ± 1.02	21 (34%)	1.25 ± 0.85
TV≥+1 (LIV caudad to TV)	43 (27%)	1.09 ± 1.04**	33 (43%)	0.96 ± 0.85	20 (32%)	1.56 ± 0.76

*CSVL = center sacral vertical line, LIV = lowest instrumented vertebra, and TV = touched vertebra. †The values are given as the mean and the standard deviation. ‡The CSVL-LIV distances between the TV groups were not significantly different (p = 0.424). §The CSVL-LIV distances between the TV groups were not significantly different (p = 0.326). #P = 0.006 when comparing the CSVL-LIV distance between the TV≥−1 and TV0 groups. **P = 0.002 when comparing CSVL-LIV distance between the TV≥−1 and TV≥+1 groups.

fusion >1 level cephalad to the TV (TV>−1) whereas 34 patients (11%) had fusion >1 level caudad to the TV (TV>+1).

Patients who had fusion cephalad to the TV had a greater 5-year CSVL-LIV distance (mean and standard deviation, 1.55 ± 1.18 cm) compared with those who had fusion to the TV (1.26 ± 0.93 cm) (p = 0.055) (Table I). Patients who had fusion >1 level cephalad to the TV had a greater 5-year CSVL-LIV distance (1.62 ± 1.31 cm) compared with those who had fusion just 1 level cephalad to the TV (1.54 ± 1.18 cm), although this difference was not significant (p = 0.18). Patients who had fusion caudad to the TV had a shorter postoperative CSVL-LIV distance (1.15 ± 0.87 cm) than those who had fusion to, or cephalad to, the TV (p = 0.055) (Table I).

In a subanalysis of patients according to the lumbar modifier, a significant difference in the postoperative CSVL-LIV distance was seen only among patients with a preoperative "A" modifier. Patients with Lenke type-1A and 2A curves who had fusion cephalad to the TV had a significantly greater CSVL-LIV distance (2.01 ± 1.48 cm) than those who had fusion to the TV (1.25 ± 0.93 cm, p = 0.006) or caudad to the TV (1.09 ± 1.04 cm, p = 0.002). In addition, the average CSVL-LIV distance in the group of patients who had fusion cephalad to the TV was 0.76 cm (61%) greater than that in the group who had fusion to the TV and 0.92 cm (84%) greater than that in the group who had fusion caudad to the TV. Among patients with "B" (n = 76, p = 0.424) or "C" (n = 62, p = 0.326) lumbar modifiers, there were no significant differences among the TV groups (Table II).

With regard to the sagittal plane, comparison of the preoperative SSV with the preoperative coronal TV showed that the preoperative SSV was cephalad to the TV in 124 patients (41.5%), at the same level as the TV in 62 patients (20.7%), and caudad to the TV in 113 patients (37.8%). Only 7 patients (2.3%) had radiographic distal junctional kyphosis at 5 years postoperatively, including 4 (3.2%) of the 124 patients in whom the SSV was cephalad to the TV, 1 (1.6%) of the 62 patients in whom it was at the same level as the TV, and 2 (1.8%) of the 113 patients in whom it was caudad to the TV. The rate of distal junctional kyphosis was not significantly between patients who had fusion cephalad to the TV and those who had fusion to the same level or caudad to the TV (p = 0.65).

Discussion

Despite advances in techniques and instrumentation, controversy still exists with regard to selection of the appropriate LIV when treating AIS with posterior spinal fusion[10-13,23]. Appropriate selection of the LIV in patients undergoing surgical treatment of AIS is of utmost importance because incorrect selection may lead to postoperative translation and angulation of the LIV, the adding-on phenomenon, and global imbalance. These malalignments can lead to degenerative changes and the need for extension of the fusion[6,14,24-31].

There is substantial debate regarding the various recommendations for LIV selection[4-9,15,16,25,26,32,33], yet there is no universally accepted rule for this crucial component of AIS surgery. Goldstein encouraged extending the fusion from the upper to the lower neutral vertebra (NV)[2,3]. Harrington recommended that the LIV remain within "the stable zone" on a standing spine radiograph[1,16], whereas Moe, King, and colleagues advocated fusing to the SV caudally[4,7,32]. Suk et al., in a study of 42 patients with major thoracic curves who underwent posterior spinal fusion with use of pedicle screw instrumentation, utilized the NV as a reference point for LIV selection and demonstrated its utility in avoiding adding-on[6]. Selection of the end vertebra (EV), NV, and SV has shown good to excellent intraobserver reliability but poor interobserver agreement between surgeons[34]. Lack of uniformity in selecting these parameters poses an obstacle in using them as references for preoperative planning and LIV determination. In a similar manner, side-bending radiographs for LIV selection depend on patient effort and radiographic technique; hence, these radiographs cannot be standardized and are subject to inherent variability[15,33].

The fundamental principle in selecting the optimal fusion level in patients with AIS is to achieve a globally balanced spine while minimizing the number of fusion levels. To achieve this goal, the LIV should be well centered over the sacrum. Selecting an LIV that is at least touched by a vertical line bisecting the sacrum is logical as such a vertebra is relatively centered over the

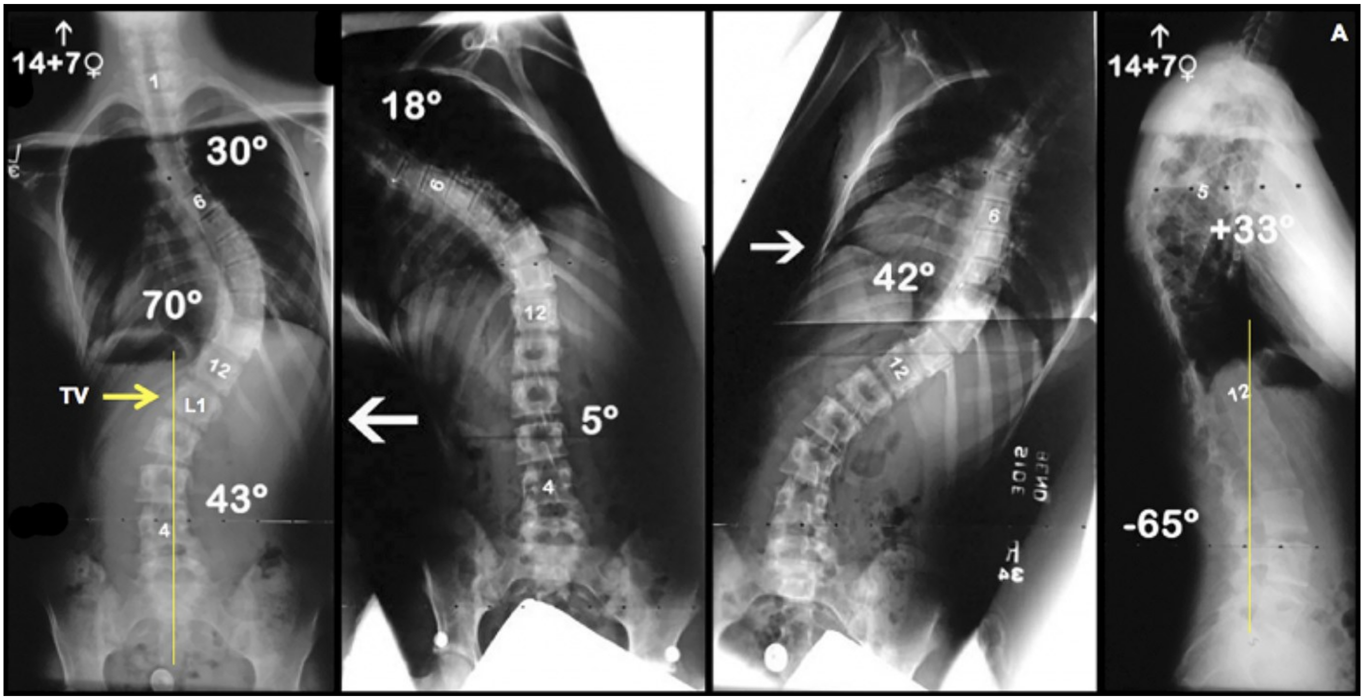

Fig. 1-A

Figs. 1-A and 1-B Radiographs of the spine of a 14-year-old girl with a 70° right-sided main thoracic AIS curve. **Fig. 1-A** Preoperative standing and bending radiographs. Both the upper thoracic curve and the thoracolumbar-lumbar curve are flexible and nonstructural. The T5-T12 kyphosis is 33°, and there is no pathological upper thoracic or thoracolumbar kyphosis. The TV is L1. With use of the third modifier, this curve would be classified as a Lenke 1AN/L1.

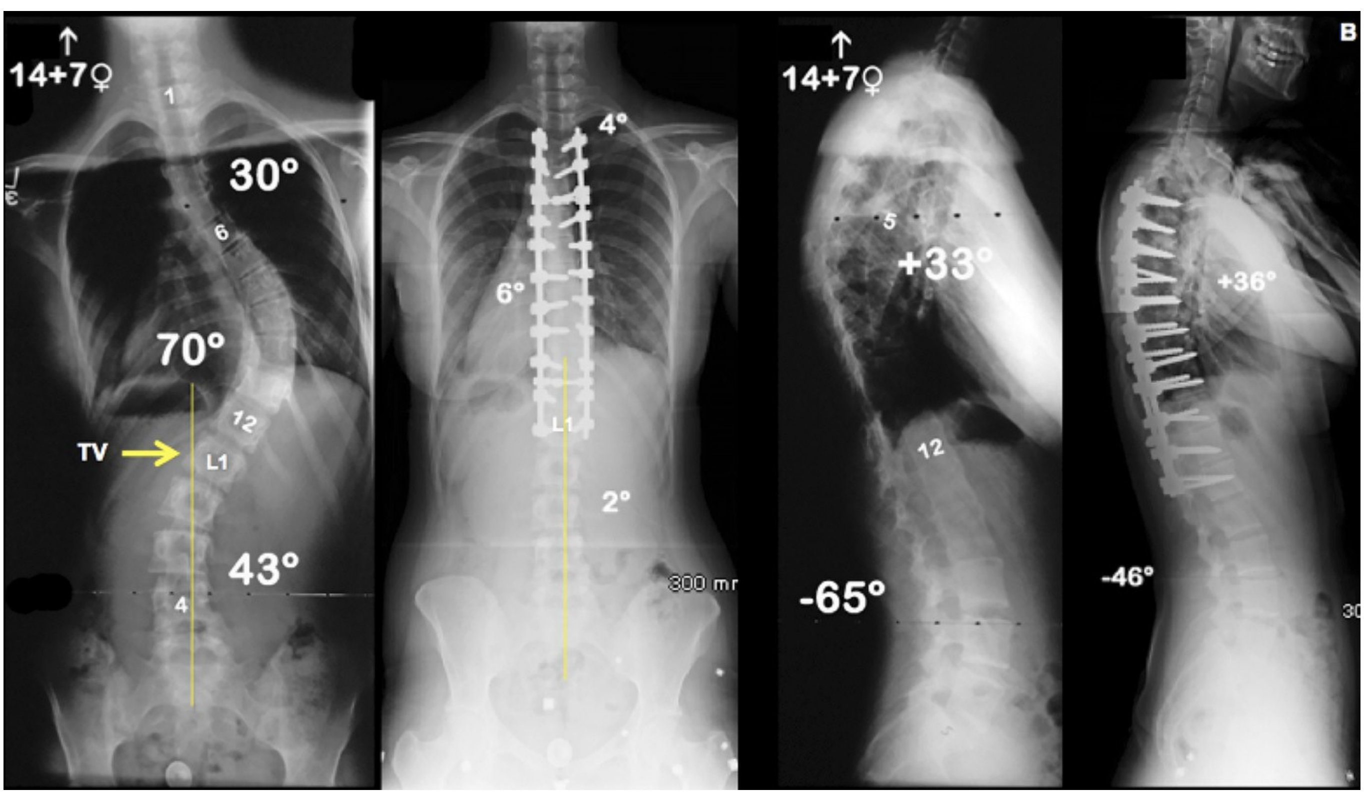

Fig. 1-B

The 5-year postoperative radiographs (second and fourth panels) demonstrated excellent correction, LIV position, and coronal balance in comparison with the preoperative radiographs (first and third panels).

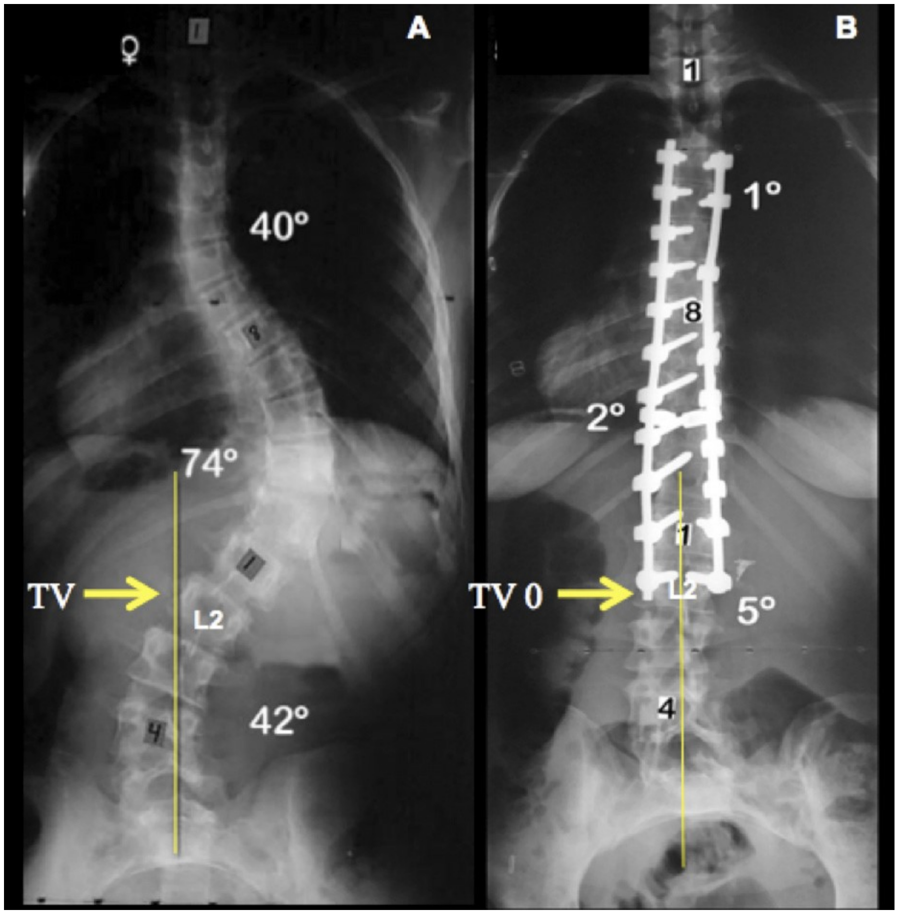

Fig. 2

Preoperative (**Fig. 2-A**) and 5-year postoperative (**Fig. 2-B**) posteroanterior radiographs of the spine of a patient with a Lenke type-1 curve with L2 as the TV (i.e., a Lenke 1AN/L2 curve). L2 was chosen as the LIV (TV0). The postoperative radiograph demonstrates excellent alignment of the LIV and coronal balance.

pelvis. Using the TV as a reference point depends only on placing the CSVL on the preoperative upright coronal radiograph and selecting the most cephalad thoracolumbar or lumbar vertebra touched by this line[9,14]. We believe that using the TV modifier in patients with AIS provides a simple universal landmark for LIV selection that is easy to understand and utilize.

The main question of the present study is whether the TV modifier, as a method of preoperative LIV selection, would produce an optimal long-term postoperative LIV position after an instrumented posterior spinal fusion in patients with Lenke type-1 and 2 curves. Among the many surgeons who contributed to the multicenter database, the TV0 level was the most common LIV regardless of the method utilized for LIV selection (Figs. 1-A, 1-B, and 2). In addition, in 35.5% of the patients, the LIV was directly (1 level) above (TV−1) or below (TV+1) the TV. Thus, in 86.6% of the patients, the LIV was selected at or immediately adjacent to the TV, confirming the TV region as an important landmark for LIV determination, even though LIV selection was performed by the treating surgeons prior to initiation of this study.

When comparing the 3 groups overall on the basis of the location of the fusion in relation to the TV, we found similar mean postoperative CSVL-LIV distances in patients who had fusion to the TV (1.26 ± 0.93 cm) and caudad to the TV (1.15 ± 0.87 cm, $p = 0.055$). In addition, fusion to TV0 resulted in a more centered LIV (1.26 ± 0.93 cm) in comparison with the position in patients who had fusion cephalad to the TV (1.55 ± 1.18 cm, $p = 0.055$). This finding reached strong significance for patients with a preoperative "A" lumbar modifier, in whom fusion to the TV appeared to produce a more centered LIV position relative to the CSVL than in patients who had fusion cephalad to the TV (Table II). While a more cephalad LIV selection preserves motion, it may place the remaining segments at a higher risk of adding-on[25]. This phenomenon has been extensively studied, with adding-on having been reported in up to 51.1% of patients with Lenke type-1A curves[6,24-26]. Although the exact radiographic determinants of adding-on have varied among studies, reported risk factors in this population have included age at the time of surgery; Risser stage; open triradiate cartilage; preoperative Cobb angle; correction rate; increased SV-LIV, NV-LIV, and EV-LIV distances; preoperative deviation of the LIV from the CSVL; and L4 vertebral tilt[13,17,24-29].

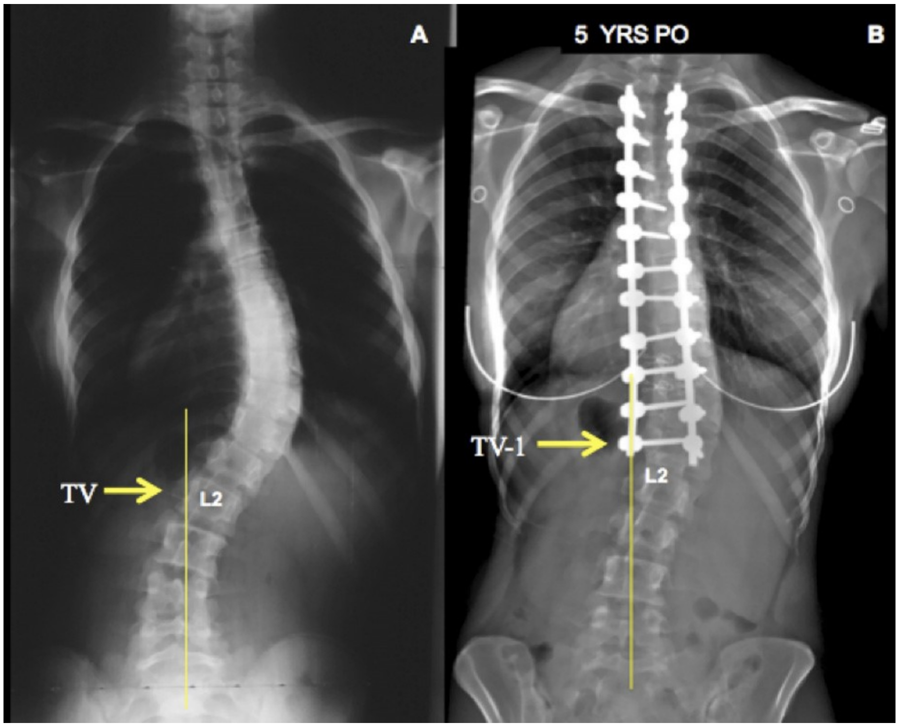

Fig. 3

Fig. 3-A Preoperative posteroanterior radiograph of the spine of a patient with a Lenke type-1 AIS curve with an L2 TV (i.e., a Lenke 1AN/L2 curve). **Fig. 3-B** Posteroanterior radiograph, made 5 years postoperatively, showing substantial translation of the LIV from the midline with resultant coronal imbalance. The LIV that had been chosen was 1 level cephalad to the TV (TV−1).

In the present study, Lenke type-1A and 2A curves that were fused cephalad to the TV had 61% and 84% more CSVL-LIV deviation than those that were fused at or caudad to the TV, respectively. Among patients with an "A" lumbar modifier, there was no advantage in selecting an LIV caudad to the TV as those patients had similar postoperative CSVL-LIV distances but fewer mobile segments in comparison with those who had fusion to the TV (Table II). This finding emphasizes the importance of choosing the TV as the LIV in this subgroup of patients in order to avoid LIV translation and potential adding-on while maximizing the number of mobile segments caudad to the fusion (Fig. 3). We did not find similar significant differences in the groups of patients with "B" and "C" lumbar modifiers. Among patients with a "B" lumbar modifier, only 8 patients had fusion cephalad to the TV, which may preclude adequate statistical analysis. Among those with a "C" lumbar modifier, there were nearly equal numbers of patients who had fusion cephalad to the TV (n = 21), to the level of the TV (n = 21), or caudad to the TV (n = 20). In 15 patients, the LIV was 2, 3, or 4 vertebrae caudad to the TV, representing patients with type-1C or 2C curve patterns in which the nonstructural thoracolumbar or lumbar curve was included in the fusion, not following selective fusion rules for 1C and 2C curves. For an equitable analysis of appropriate LIV selection in patients with type-1C and 2C curves, these 15 patients were eliminated as theoretically they should undergo a main thoracic or upper thoracic/main thoracic selective fusion according to the Lenke classification system[8]. With the exclusion of these outliers, 43 (91.5%) of 47 patients with Lenke type-1C and 2C curves were fused to the TV or immediately adjacent to the TV, further supporting the TV as an important landmark for LIV selection in this group.

The multicenter, multisurgeon nature of this review should exclude bias related to the use of the TV as the LIV for patients with type-1 and 2 AIS curves as there had been no discussion regarding this parameter before the dates of the surgical procedures. Thus, whether consciously or unconsciously, surgeons selected the TV as the LIV in >50% of the cases and in close to 87% of all cases if we include the vertebrae immediately adjacent to the TV (TV−1 and TV+1). The intraoperative correction method may play a role in LIV positioning and was not controlled in these patients. Our study defines the TV as an important landmark in LIV selection and strongly supports the use of the TV as a third modifier in the Lenke classification system for AIS.

Although postoperative disc angulation and coronal balance may play a role in ultimate LIV positioning, we did not evaluate these variables. Asymmetrical discs and those immediately adjacent to a fusion exhibit increased intradiscal pressure, predisposing them to disc degeneration and potentially furthering LIV translation[30,31,35]. The long-term follow-up in the present study confirmed the final coronal LIV position relative to the CSVL as early postoperative variances and changes related to continued spinal growth should have been completed by the 5-year postoperative period that we analyzed.

Lateral full-spine radiographs showed that the percentage of patients who developed distal kyphosis at 5-years was relatively low when compared with other studies[19,22]. By definition, Lenke type-1 and 2 curves lack marked preoperative thoracolumbar kyphosis (>20°) as that would make the thoracolumbar or lumbar curve structural, changing the classification to type-3 (double-major) or 4 (triple-major) curves[8]. The sagittal posture in patients with AIS is not constrained and varies widely on the basis of arm position and hip and/or lumbar spine extension, among other factors. Coronal plane alignment is relatively fixed and a landmark based in this plane should yield more reproducible results.

The sagittal plane alignment, the SSV, and the last touched sagittal vertebra do play an important role in appropriate LIV selection in the treatment of both kyphotic spine deformities and AIS, as they may help minimize the risk of distal junctional kyphosis[18,19]. We did not find a significant relationship between the SSV and the TV in our cohort. Another study will be performed to determine whether the SSV affects LIV selection when chosen by the coronal TV in patients with Lenke type-3 to 6 curves.

Conclusions

In this multicenter, multisurgeon review of patients with Lenke type-1 and 2 AIS curves and a minimum of 5 years of follow-up, the TV or a vertebra adjacent to the TV (TV−1 or TV+1) was selected as the LIV in close to 90% of patients. Selecting the TV as the LIV for Lenke type-1A and 2A curves produced acceptable LIV positioning at the time of long-term follow-up, whereas fusion cephalad to the TV significantly increased CSVL-LIV translation, potentially increasing the risk of adding-on and coronal decompensation. Understanding and utilizing the TV as the third modifier of the Lenke AIS classification system provides an important landmark in the preoperative planning for all type-1 and 2 AIS curves and assists the surgeon in proper LIV selection, especially for patients with an "A" lumbar modifier. ■

Note: Harms Study Group Investigators include: Aaron Buckland, MD, New York University; Amer Samdani, MD, Shriners Hospitals for Children—Philadelphia; Amit Jain, MD, Johns Hopkins Hospital; Baron Lonner, MD, Mount Sinai Hospital; Benjamin Roye, MD, Columbia University; Burt Yaszay, MD, Rady Children's Hospital; Chris Reilly, MD, BC Children's Hospital; Daniel Hedequist, MD, Boston Children's Hospital; Daniel Sucato, MD, Texas Scottish Rite Hospital; David Clements, MD, Cooper Bone & Joint Institute New Jersey; Firoz Miyanji, MD, BC Children's Hospital; Harry Shufflebarger, MD, Nicklaus Children's Hospital; Jack Flynn, MD, Children's Hospital of Philadelphia; Jahangir Asghar, MD, Paley Orthopedic & Spine Institute; Jean Marc Mac-Thiong, MD, CHU Sainte-Justine; Joshua Pahys, MD, Shriners Hospitals for Children—Philadelphia; Juergen Harms, MD, Klinikum Karlsbad-Langensteinbach, Karlsbad; Keith Bachmann, MD, University of Virginia; Lawrence Lenke, MD, Columbia University; Mark Abel, MD, University of Virginia; Michael Glotzbecker, MD, Boston Children's Hospital; Michael Kelly, MD, Washington University; Michael Vitale, MD, Columbia University; Michelle Marks, PT, MA, Setting Scoliosis Straight Foundation; Munish Gupta, MD, Washington University; Nicholas Fletcher, MD, Emory University; Patrick Cahill, MD, Children's Hospital of Philadelphia; Paul Sponseller, MD, Johns Hopkins Hospital; Peter Gabos, MD, Nemours/Alfred I. duPont Hospital for Children; Peter Newton, MD, Rady Children's Hospital; Peter Sturm, MD, Cincinnati Children's Hospital; Randal Betz, MD, Institute for Spine & Scoliosis; Ronald Lehman, MD, Columbia University; Stefan Parent, MD, CHU Sainte-Justine; Stephen George, MD, Nicklaus Children's Hospital; Steven Hwang, MD, Shriners Hospitals for Children—Philadelphia; Suken Shah, MD, Nemours/Alfred I. duPont Hospital for Children; Tom Errico, MD, Nicklaus Children's Hospital; and Vidyadhar Upasani, MD, Rady Children's Hospital.

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